Fermi National Accelerator Laboratory

FERMILAB-Pub-87/219-E

[E-691]

A Study of D^0- $\overline{D}^0$ Mixing*

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December 10, 1987

*Submitted to Phys. Rev. Lett.

A STUDY OF $D^0 - \overline{D}^0$ MIXING

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ABSTRACT

We present a study of D^0 mixing from Fermilab experiment E691, using events of the type $D^{*+} \to \pi^+ D^0$, with $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$. The decay time is used to separate mixing from doubly Cabibbo-suppressed decays. We observe no evidence for mixing in either mode. Combining the results from the two decay modes, we find $r_M = 0.0005 \pm .0020$ or $r_M < .0037$ at the 90% confidence level, where r_M is the ratio of wrong sign decays from mixing to right sign decays. We also present limits on doubly Cabibbo suppressed decays and consider the effect of possible interference.

10 December 1987
PACS 12.15.Ff, 13.25.+m, 14.40.Jz
Submitted to Physical Review Letters

Recent observations of $\Delta S = 2$ double tagged D^0 decays by the MARK III collaboration,[1] have been interpreted to indicate the presence of substantial mixing in the $D^0\overline{D}^0$ system.[2] If the MARK III events are due entirely to mixing, then $r = r_M \sim 1\%$, where r = $B(D^0 \rightarrow \overline{f})/B(D^0 \rightarrow f)$, f is the usual S = -1 final state, and $\overline{f}$ is its charge conjugate. Although Standard Model calculations based on the box diagram[3] predict $D^0 - \overline{D}^0$ mixing far below current experimental sensitivity, extensions of the Standard Model[4] or long distance contributions which cannot be reliably calculated in perturbation theory,[5,6] could give rise to observable mixing. The interpretation of hadronic D^0 decays with wrong strangeness ($D^0 \rightarrow K^+\pi^-$, for example) is complicated by the presence of doubly Cabibbo-suppressed decays (DCSD). The rate for such processes is expected to be $O(\tan^4\theta_c) \sim 0.3\%$, but might be significantly enhanced in particular hadronic final states.

This paper presents results from an analysis of the full data sample of the Fermilab photoproduction experiment E-691.[7,8] Using a high precision vertex detector in the Tagged Photon Spectrometer, we observe large samples of $D^{*+} \rightarrow D^0\pi^+ \rightarrow [K^-\pi^+]\pi^+$ and $D^{*+} \rightarrow D^0\pi^+ \rightarrow [K^-\pi^+\pi^-\pi^+]\pi^+$ and charm conjugate events, which have exceptionally low background. We search for mixing in the sample of D^* events with wrong sign, that is, the wrong combination of charge and strangeness: $D^{*+} \rightarrow D^0\pi^+ \rightarrow [K^+\pi^-]\pi^+$ or $[K^+\pi^-\pi^+\pi^-]\pi^+$. The charge of the pion from the D^* decay tags the charm quantum number of the D^0 at production. The proper time of the decay is used to separate mixing from DCSD.

The events are reconstructed in a silicon microstrip detector-drift chamber tracking system and Čerenkov counter information is used to identify particles. The charmed particle decay tracks are required to form a vertex with a good χ^2. In the analysis of the $K\pi$ channel we search for a primary vertex that lies within a transverse distance of 80 μm of the line of the flight of the D^0 candidate and require that it either contain the bachelor pion (i.e. the pion which accompanies the D^0) or lie close to the projected position of the bachelor pion track. We reject the event if more than one extra track has an impact parameter which is less than 80 μm with respect to the secondary vertex.

The $K\pi\pi\pi$ candidates are subjected to slightly more stringent cuts to reduce the larger combinatorial background. We require the primary vertex to lie within $65\mu m$ of the line of flight of the D^0 and demand that the bachelor pion pass through the primary vertex. The event is rejected if any extra track passes within $80\mu m$ of the charm decay vertex, or if any track in the secondary vertex passes significantly closer to the primary vertex than to the secondary vertex.

The final samples include all such events with $t > 0.22$ psec, 1.75 GeV $\leq M(D^0) \leq$ 2.0 GeV, and 1 MeV $\leq Q \leq$ 30 MeV where t is the proper time of the D^0 decay calculated from the primary vertex, and $M(D^0) = M(K\pi)$, $[M(K\pi\pi\pi)]$ is the invariant mass of the D^0 candidate. The quantity $Q = M(D^*) - M(D^0) - M(\pi^+)$, is the available rest mass energy in the D^{*+} decay where $M(D^*) = M(K^-\pi^+\pi^+), [M(K^-\pi^+\pi^-\pi^+\pi^+)]$ is the invariant mass of the D^* candidate.

The best measure of the effectiveness of the D^* selection is the size of the signal and background in the right sign $(K^-\pi^+\pi^+)$ events. Figure 1(a) shows a scatter plot of Q versus $M(K\pi)$ for the right sign sample, with $t > 0.22$ psec, which corresponds to about $\tau_{D^0}/2 = 1/(2\Gamma)$. Inside the boxed region there are 611 events, including about 7 events from D^0's combined with random pions and 5 other background events. In the vertical direction above the signal region, a band of D^0 events combined with random pions is visible. A band of D^* events in which the D^0 does not decay into the $K\pi$ state (i.e., one of the decay products is misidentified or not detected) is evident in the horizontal direction to the left of the boxed area. Figure 1(b) shows the same scatter plot for wrong sign events $(K^+\pi^-)\pi^+$, with no excess of events in the D^* region. A similar plot in the $K\pi\pi\pi$ channel shows 375 ± 19 events in the right sign mode, with similar backgrounds to the $K\pi$ mode. There is no significant excess in the wrong sign plot.

In order to separate mixing from DCSD and from background we use the decay time information. As in the case of the K^0, the D^0 system can be characterized by two CP eigenstates (even or odd) with mass difference ΔM and width difference $\Delta\Gamma$. We use the convention $\Delta\Gamma = \Gamma_{odd} - \Gamma_{even}$, $\Delta M = M_{odd} - M_{even}$. In the limit ΔM, $\Delta\Gamma << \Gamma$, the rate for wrong-sign decays has the time dependence:[9]

$$(1.1) \qquad I(D^0 \to K^+\pi^-) = e^{-\Gamma t}\left\{\frac{t^2}{4}[(\Delta M)^2 + (\frac{1}{2}\Delta\Gamma)^2] + |\rho|^2 + t[\frac{1}{2}(\Delta\Gamma)Re\,\frac{1-\epsilon}{1+\epsilon}\rho \mp \Delta M\; Im\,\frac{1-\epsilon}{1+\epsilon}\rho]\right\}$$

where ϵ is the CP parameter familiar from K^0 decay. The $-$ $(+)$ sign in the fifth term is taken for wrong sign $D^0(\overline{D}^0)$ decays and thus averages to zero in a sample with equal numbers of D^0s and $\overline{D^0}$s. This term is also explicitly CP violating and is therefore neglected. The fourth term takes into account possible interference between the mixing and DCSD amplitudes, which is expected to be small. The third term is due to DCSD, and is described by the ratio of amplitudes $\rho = A(D^0 \to \overline{f})/A(D^0 \to f)$ where $f = K^-\pi^+$ $[K^-\pi^+\pi^-\pi^+]$. The ratio ρ can be expressed in terms of Kobayashi-Maskawa matrix elements: $\rho \approx V_{cd}V_{us}/V_{cs}V_{ud}$. It is expected[9] to be roughly equal to $-\tan^2\theta_c$. The first and second terms are due to mixing. The initial analysis of wrong sign decays includes the first three terms only, because interference is expected to be a small effect.

The parameter r has the value $r_M = [(\Delta M)^2 + (\frac{1}{2}\Delta\Gamma)^2]/2\Gamma^2$ if the wrong-sign decays are due solely to mixing, and $r = r_{2C} = |\rho|^2$ if they are due solely to DCSD. The mixing events have a time distribution proportional to $t^2\exp(-\Gamma t)$, while the DCSD distribution is the usual $\exp(-\Gamma t)$. Thus if we cut at $t > 2\tau_{D^0} = 2/\Gamma$, about 68% of the events due to mixing are kept, but only 14% of the DCSD events are retained. Such a cut also reduces the non-charm background to a negligible level.

Figure 2 shows scatter plots for the $K\pi$ mode with the additional selection $t > 0.88$ psec $\simeq 2/\Gamma$. In Figure 2(a) there is still a strong D^* signal from the long-lived tail of the right sign decays. In Figure 2(b) there should be 2.7 background events in the boxed region if there is no mixing, 2.2 due to D^0's which combine with random pions and 0.5 due to uncorrelated combinatorial background. There is only one event in the signal box (and 3 events near the border of the box), consistent with no mixing. If $r_M = 1\%$, where r_M is the fraction of wrong sign events due to mixing, there would be about 11 events at the D^*. Figures 3(a),(b) show the analogous plots for the $K\pi\pi\pi$ mode. The two events in the boxed area are consistent with no mixing.

To extract the best values for the number of events in the data sample from each source, we perform a maximum likelihood fit to all the events using Q, $M(K\pi)$, and t for each event. In the right-sign fit, there are four components, each with a known dependence on these three variables: $f_{RS} = f_A + f_B + f_C + f_D$. (A) The D^* events are described by Gaussians in Q and $M(K\pi)$, and a time dependence which is $\exp(-\Gamma t)$, modified slightly by the acceptance. (B) D^0 events with random pions have the same form, except that the Q spectrum does not have a peak. (C) The D^* events in which the D^0 does not decay into $K\pi$ produces a continuous $M(K\pi)$ spectrum on the low side of the D^0. (D) Finally, there is a background due to random combinations of pions and kaons, which is described by a phase space dependence on Q, and a decreasing linear term in $M(K\pi)$. The fit gives a total of 709 ± 28 D^* events of which 611 are in the region 4.3 MeV$< Q <$ 7.3 MeV and 1.845$<$ M $<$ 1.885 GeV. The dominant backgrounds in this region are 7.3 events of type (B) and 4.7 events of type (D).

The fit to the wrong-sign sample includes terms with the same dependence as terms (A), (B), and (D) of the right-sign fit: $f_{WS} = f_A + f_B + f_D + f_{MIX}$. The additional fourth term has the same Q and $M(K\pi)$ dependence as term (A), but represents mixing and therefore has a $t^2 \exp(-\Gamma t)$ dependence. Finally, there is a small contribution, with fixed normalization, from right-sign decays in which both the K and π are misidentified. These events have a very broad peak in $M(K\pi)$, with less than two events expected in the signal region from this source. The results of the fit are 0.8 ± 6.0 DCSD events and 1.2 ± 3.6 events from mixing. The background terms, (B) and (D), are consistent with the same terms in the right-sign sample, as expected.

These results are for the region $t > 0.22$ psec, and must be corrected for the time dependence of the efficency to obtain the final physics result. The dominant part of this correction is due to the the requirement $t > 0.22$ psec. As the time dependence of mixing is proportional to $t^2 e^{-\Gamma t}$, the corrected number of mixed events, 1.4 ± 4.1, is only slightly greater than the uncorrected number. The corrected number of right-sign D^* events is 1554.1 ± 53.5, which implies $r_M = (1.4 \pm 4.1)/(1554.1 \pm 53.5) = .0009 \pm .0026$. The 90% confidence level upper limit for the $K\pi$ mode only is then $r_M < 0.0050$. For the DCSD signal, the corrected number of events is 1.8 ± 13.2 which corresponds to a 90% confidence level upper limit of $r_{2C} < 1.5\%$ where r_{2C} is the ratio of wrong sign decays from the doubly Cabibbo-suppressed process to right sign decays.

We have performed a similar fit to the events in the $K\pi\pi\pi$ sample. In this case the contribution from doubly misidentified decays is negligible. A term of type (C) is also omitted. The final result corrected to zero time is 0.0 ± 4.0 mixed events and 1357 ± 67 right sign D^* decays. This corresponds to a limit of $r_M < .0048$ at the 90% confidence level. The fit finds 5.1 ± 12.2 DCSD events, which corresponds to an upper limit of $r_{2C} < 1.8\%$ at the 90% confidence level.

To accommodate the possibility of interference between the DCSD amplitude and the mixing amplitude, we add the fourth term from equation [1.1] to the fit. The fourth term is proportional to $\sqrt{r_{2C}}\sqrt{r_M}\cos\phi$ where $\cos\phi = \frac{1}{2}\Delta\Gamma/[(\Delta M)^2 + (\Delta\Gamma/2)^2]^{1/2}$. The results of the fit to the $K\pi\pi\pi$ and $(K\pi)$ modes allowing for constructive and destructive interference are shown in Table I, where the results for the $K\pi$ mode are given in parentheses. If the sign of $\Delta\Gamma\rho$ is negative, interference can cause relatively large DCSD and mixing terms to cancel in the region near $t \simeq 2/\Gamma$. Even in the most extreme case, however, the limit on mixing is quite restrictive. Similar results are obtained for the $K\pi$ mode, but with somewhat weaker limits.

There are a number of reasons why a scenario with maximal destructive interference is unlikely. It would require a large $|\Delta\Gamma|$, but a small value of ΔM. In addition, the sign of $\Delta\Gamma\rho$ must be negative, although a simple theoretical estimate suggests that $\Delta\Gamma\rho$ is positive.[9] To properly mask the effect of mixing near $t \approx 2/\Gamma$, r_{2C} must be roughly a few percent, or $10\tan^4\theta_c$, which would be a surprising deviation from the standard picture of Cabibbo suppression. Finally, this greatly enhanced r_{2C} would have to be the same in both modes, in contrast to the situation in the measured singly Cabibbo suppressed modes. Other experiments which seek to constrain the strength of mixing by studying wrong sign hadronic D^0 modes without decay time information measure only $r = r_M + r_{int} + r_{2C}$ (r_{int} is defined as the ratio of wrong sign decays from interference to right sign decays) and are even less sensitive to mixing in this pathological case.

We observe no evidence of mixing in the $D^0 \to K\pi$ and $D^0 \to K\pi\pi\pi$ modes, and measure the parameter $r_M = .0005 \pm .0020$, corresponding to $r_M < .0037$ at the 90% confidence level. This result is inconsistent with the value of $r_M \approx 1\%$ suggested by the mixing interpretation of the Mark III events. In addition, we find limits on DCSD decays $B(D^0 \to K^+\pi^-) < 0.06\%$ and $B(D^0 \to K^+\pi^-\pi^+\pi^-) < 0.15\%$ at the 90% confidence level.

We thank the staffs of all the participating institutions. This research was supported by the U.S. Department of Energy, by the Natural Science and Engineering Research Council of Canada, by the National Research Council of Canada, and by the Brazilian Conselho Nacional de Desenvolvimento Científico e Technológico. We would like to thank I.I. Bigi for useful discussions.

REFERENCES

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1. G. Gladding, Proceedings of the Fifth International conference on Physics in Collision, Autun, France (1985).
2. I. Bigi and A.I. Sanda, Phys. Lett. 171B, 320 (1985).
3. L.-L. Chau, Phys. Rep. 95, 2 (1983).
4. A. Datta, Phys. Lett. 154B, 287 (1985).
5. L. Wolfenstein, Phys. Lett. 164B, 170 (1985).
6. J.F. Donoghue *et al.*, Phys. Rev. D33, 179 (1986).
7. J.C. Anjos *et al.*, Phys. Rev. Lett., 58, 4 (1987).
8. J.R. Raab *et al.*,Fermilab-PUB-87-144, submitted to Phys. Rev. D.(1987).
9. I.I. Bigi, SLAC-PUB-4349, June (1987), to appear in the Proceedings of the Beijing Charm Physics Symposium.

FIGURE CAPTIONS

Fig. 1 (a) The scatter plot of $Q = M(K\pi\pi) - M(\pi) - M(K\pi)$ vs. $M(K\pi)$ for the $K^-\pi^+\pi^+$ (and charm conjugate) sample. There is a requirement that $t > 0.22$ ps, where t is the proper decay time. (b) The same plot for $K^-\pi^+\pi^-$ events.

Fig. 2 (a) The scatter plot of Q vs. $M(K\pi)$ for $K^-\pi^+\pi^+$ events, with the requirement $t > 0.88$ ps. (b) The plot for $(K^-\pi^+)\pi^-$ events with $t > 0.88$ ps.

Fig. 3 (a) The scatter plot of Q vs. $M(K\pi\pi\pi)$ for $K^-\pi^+\pi^-\pi^+\pi^+$ events, with the requirement $t > 0.88$ ps. (b) The plot for $(K^-\pi^+\pi^-\pi^+)\pi^-$ events with $t > 0.88$ ps.

Table 1. Limits on mixing in the case of interference for the $K\pi\pi\pi$ and $(K\pi)$ modes at the 90% C.L.

$\cos\phi$	r_M	r_{2C}	r
1.0	0.7% (1.9%)	3.3% (4.9%)	2.6% (3.4%)
0.5	0.6% (0.6%)	2.2% (1.8%)	2.2% (1.8%)
0.0	0.5% (0.5%)	1.8% (1.5%)	1.8% (1.5%)
−0.5	0.5% (0.5%)	1.8% (1.6%)	1.8% (1.6%)
−1.0	0.4% (0.5%)	1.8% (1.6%)	1.8% (1.6%)

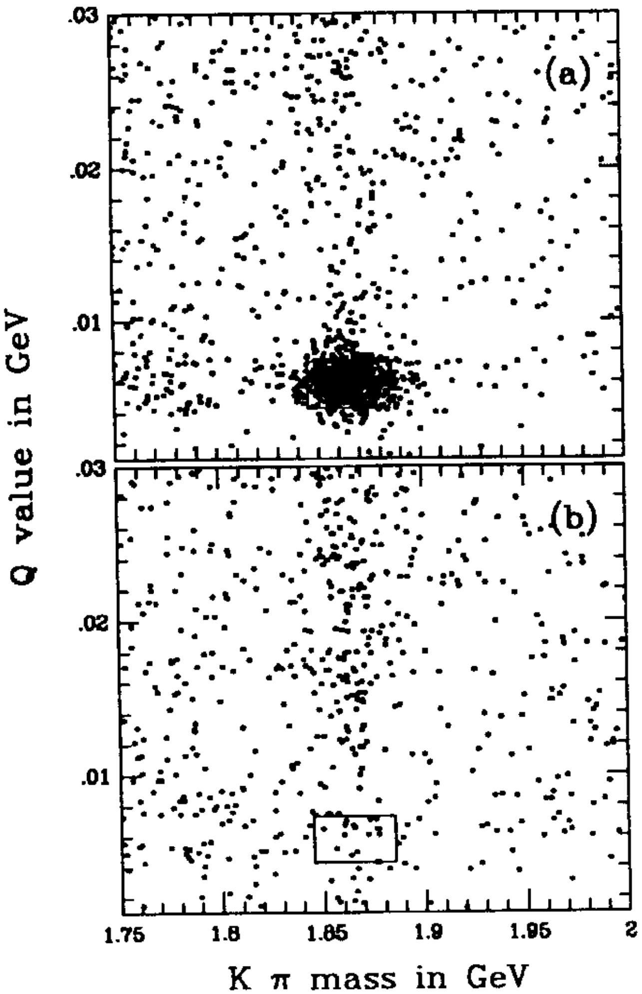

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Illustration 1 (a), (b)

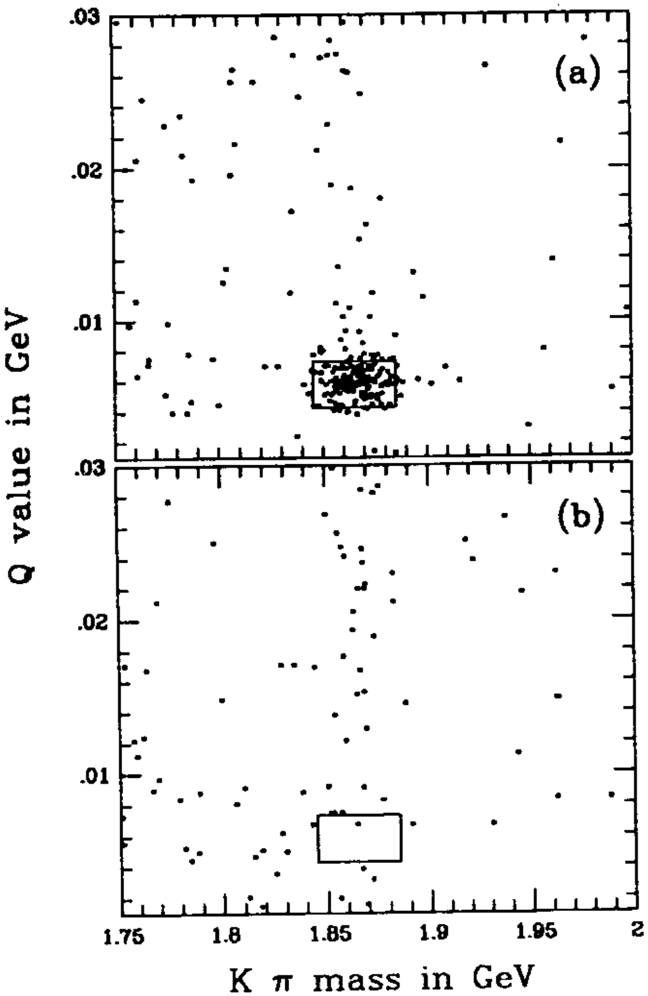

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Illustration 2 (a), (b)

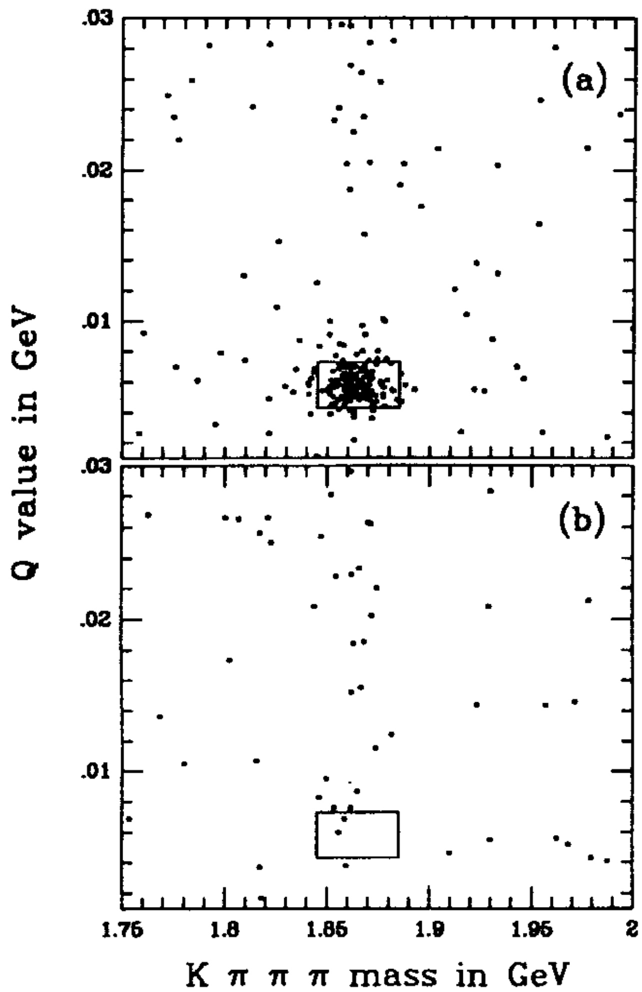

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Illustration 3 (a), (b)